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**Shi et al.**

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(54) **MODULAR ANTENNA SYSTEMS AND RELATED METHODS OF MANUFACTURE**

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**H01Q 21/00** (2006.01)  
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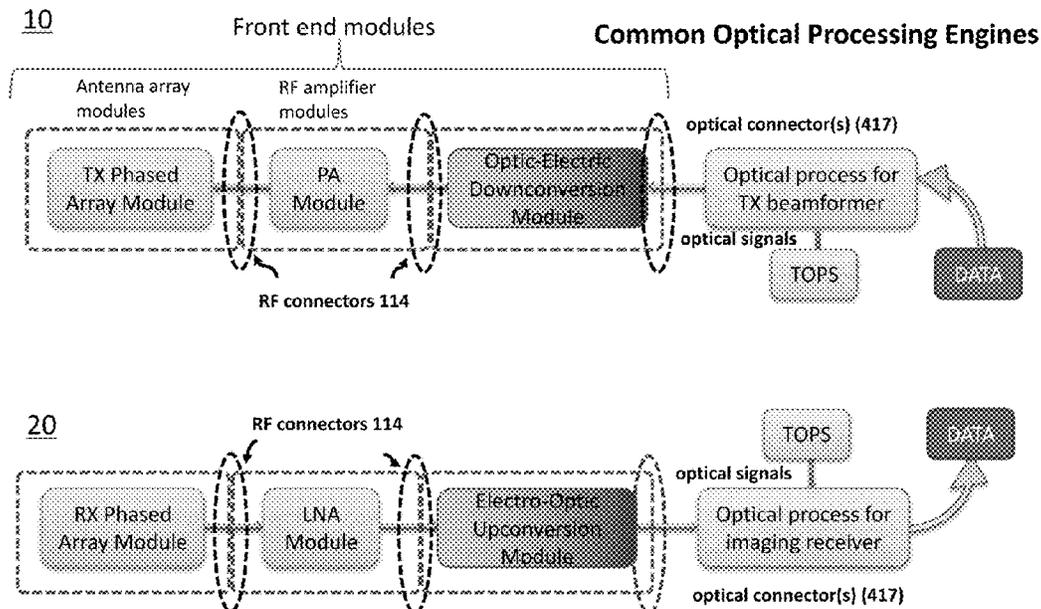
(56) **References Cited**  
**U.S. PATENT DOCUMENTS**  
4,739,334 A \* 4/1988 Soref ..... H01Q 3/2676 342/368  
6,310,992 B1 \* 10/2001 Gehrke ..... H04B 10/801 398/151  
(Continued)

**OTHER PUBLICATIONS**  
Shouyuan Shi, "Conformal Wideband Optically Addressed Transmitting Phased Array With Photonic Receiver," Sep. 1, 2014, Journal of Lightwave Technology, vol. 32, No. 20, Oct. 15, 2014, pp. 3468-3475.\*  
(Continued)

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(57) **ABSTRACT**  
Disclosed herein is a swappable modular-based radio-frequency (RF) frontend that is reconfigurable to form transmitting (TX) and receiving (RX) phased array systems for diverse applications. Such swappable RF frontend may be used with unique spatial and spectral optical processing of complex RF signals over an ultra-wide frequency band. The swappable RF front end may be used in conjunction with an optically upconverted imaging receiver and/or in conjunction with optically addressed phased array technologies transmitters.

**57 Claims, 9 Drawing Sheets**



**Related U.S. Application Data**

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- (60) Provisional application No. 62/590,066, filed on Nov. 22, 2017, provisional application No. 62/589,534, filed on Nov. 21, 2017.

2012/0230685	A1 *	9/2012	Jung .....	H04B 10/58 398/43
2014/0022119	A1 *	1/2014	Lohr .....	G01S 13/86 342/25 R
2017/0025749	A1 *	1/2017	Frye .....	H01Q 21/0025
2018/0102849	A1 *	4/2018	Morton .....	G02B 27/00
2021/0006333	A1 *	1/2021	Morton .....	G02B 6/12004
2021/0028534	A1 *	1/2021	Liu .....	H01L 23/66

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(52) **U.S. Cl.**

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(56) **References Cited**

U.S. PATENT DOCUMENTS

11,564,020	B1 *	1/2023	Xu .....	H04Q 11/0005
2006/0079290	A1 *	4/2006	Seto .....	H04B 7/086 455/562.1
2006/0239312	A1 *	10/2006	Kewitsch .....	H01S 5/42 372/29.016
2010/0278538	A1 *	11/2010	Guidotti .....	H04B 10/90 398/115

OTHER PUBLICATIONS

Luc Pastur, "Two-dimensional optical architectures for the receive mode of phased-array antennas," May 10, 1999, vol. 38, No. 14, Applied Optics, vol. 38, No. 14, pp. 3105-3107.\*

Andrew Townley, "A 94-GHz 4TX-4RX Phased-Array FMCW Radar Transceiver With Antenna-in-Package," Mar. 30, 2017, IEEE Journal of Solid-State Circuits, vol. 52, No. 5, May 2017, pp. 1245-1253.\*

SungWon Chung, "A Monolithically Integrated Large-Scale Optical Phased Array in Silicon-on-Insulator CMOS," Oct. 18, 2017, IEEE Journal of Solid-State Circuits, vol. 53, No. 1, Jan. 2018, pp. 275-292.\*

Dennis T., "Multiwavelength Optically Controlled Phased-Array Antennas," Jan. 1998, IEEE Transactions on Microwave Theory and Techniques, vol. 46, No. 1, Jan. 1998, pp. 108-113.\*

Stavros Iezekiel, "RF Engineering Meets Optoelectronics," Jul. 30, 2015, IEEE Microwave Magazine ( vol. 16, Issue: 8, Sep. 2015), pp. 28-32.\*

\* cited by examiner

FIG. 1

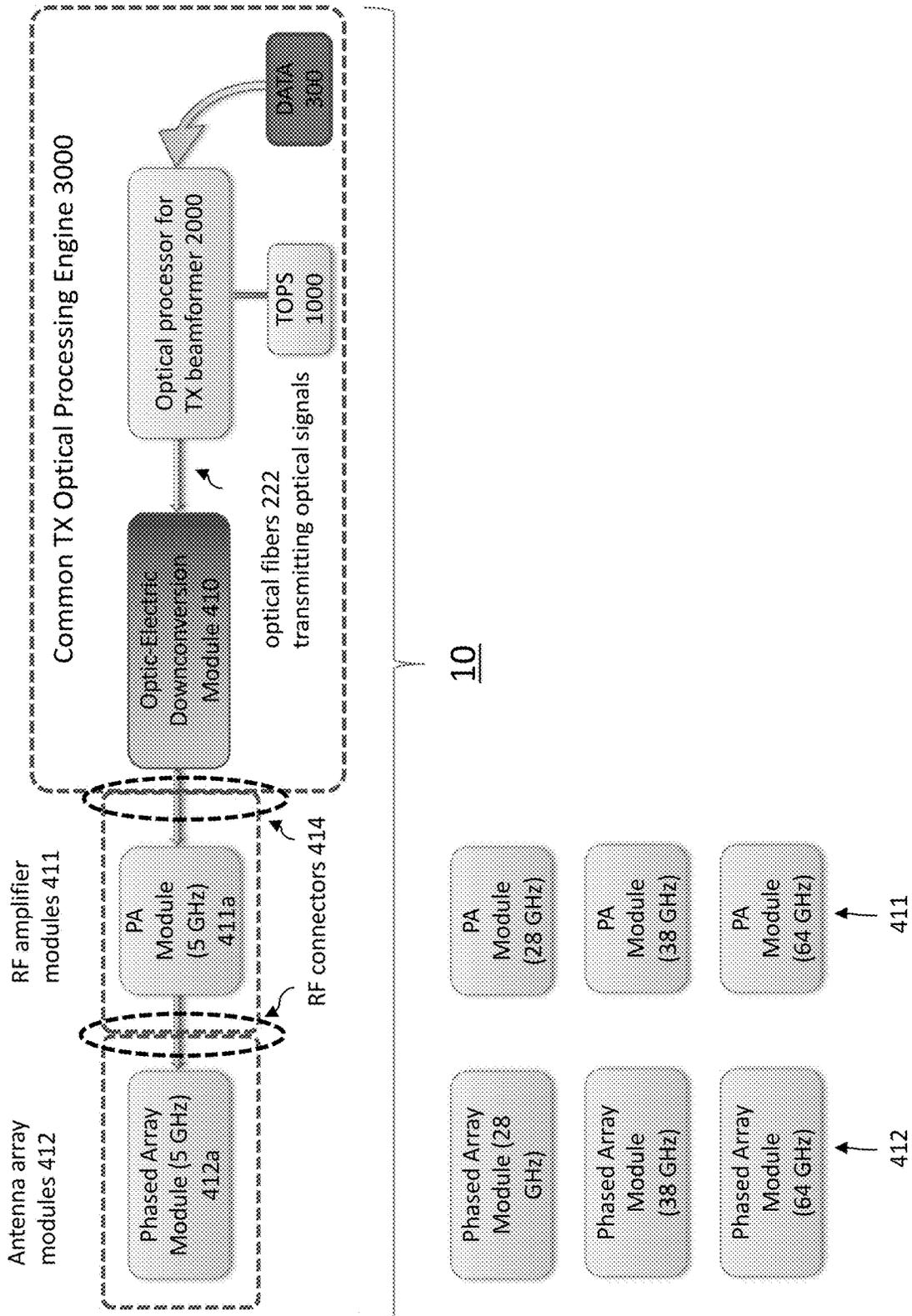


FIG. 2

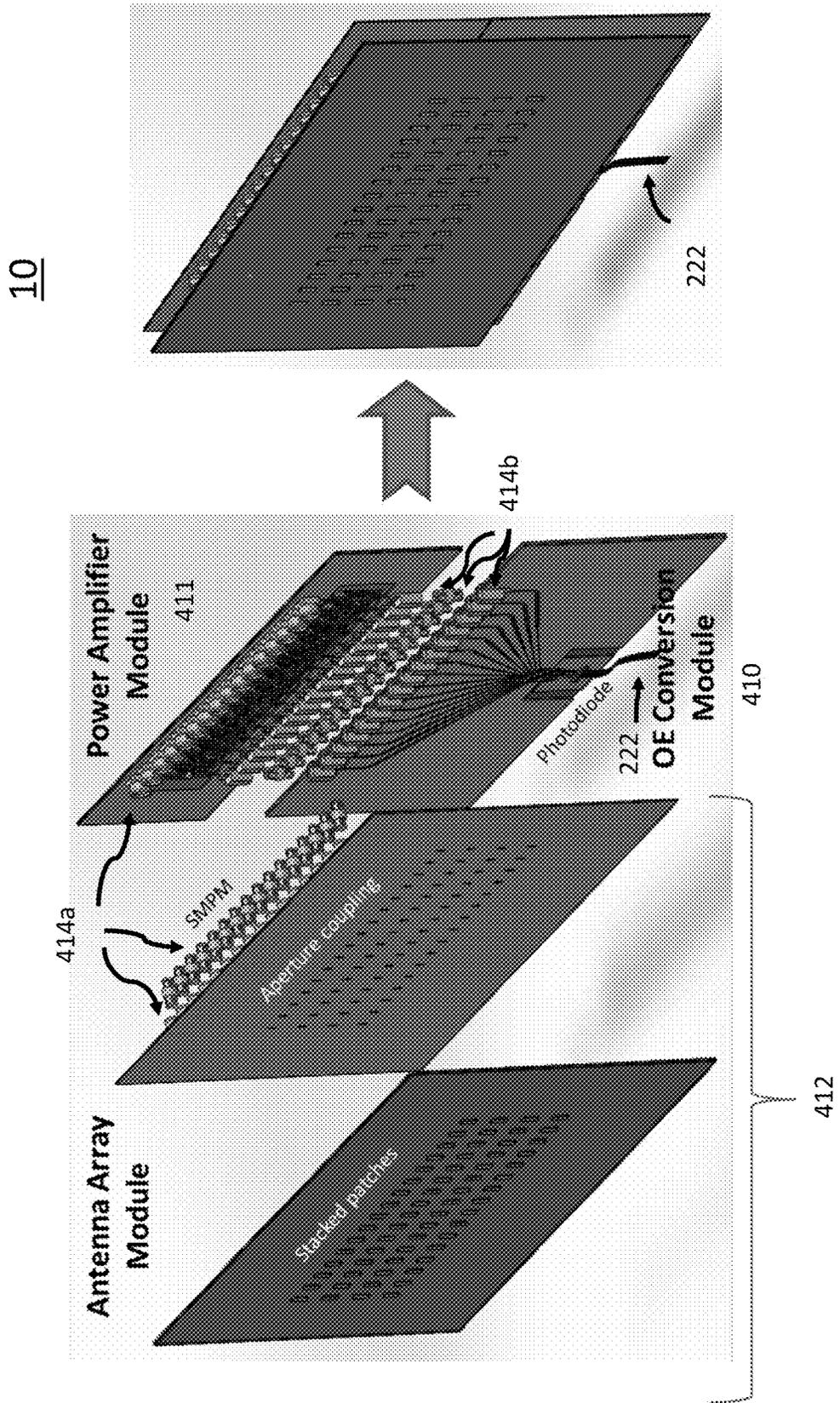
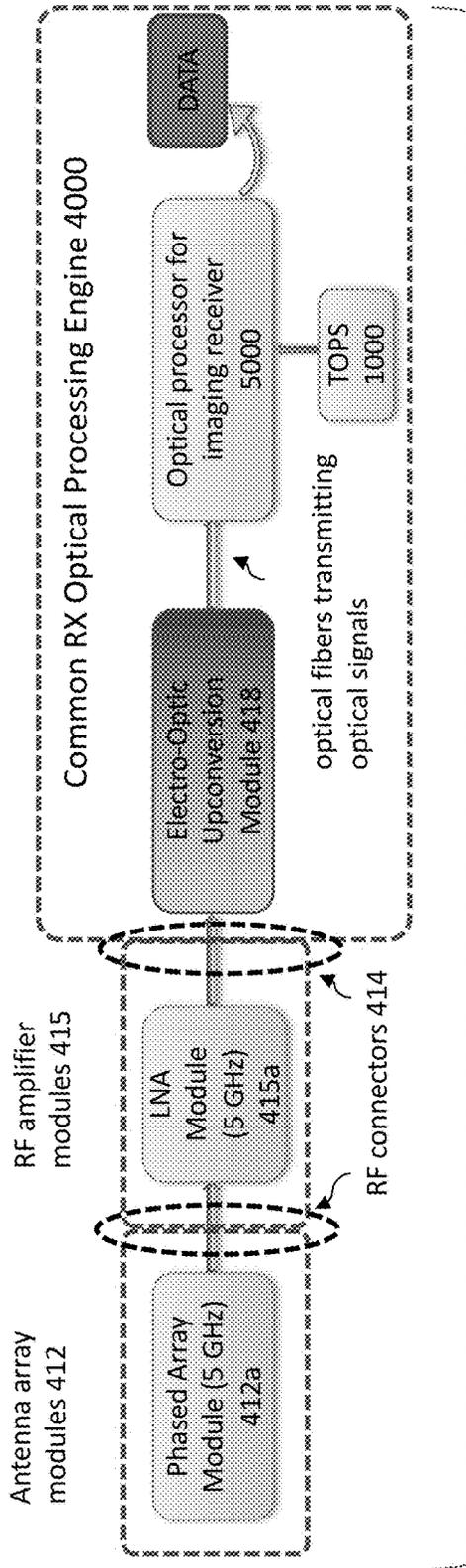


FIG. 3



20

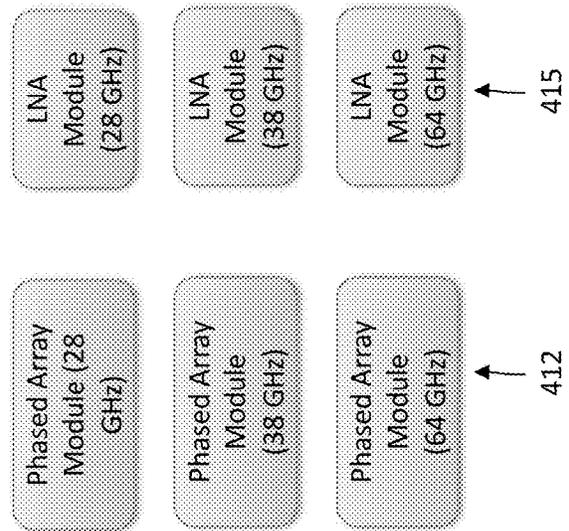


FIG. 4

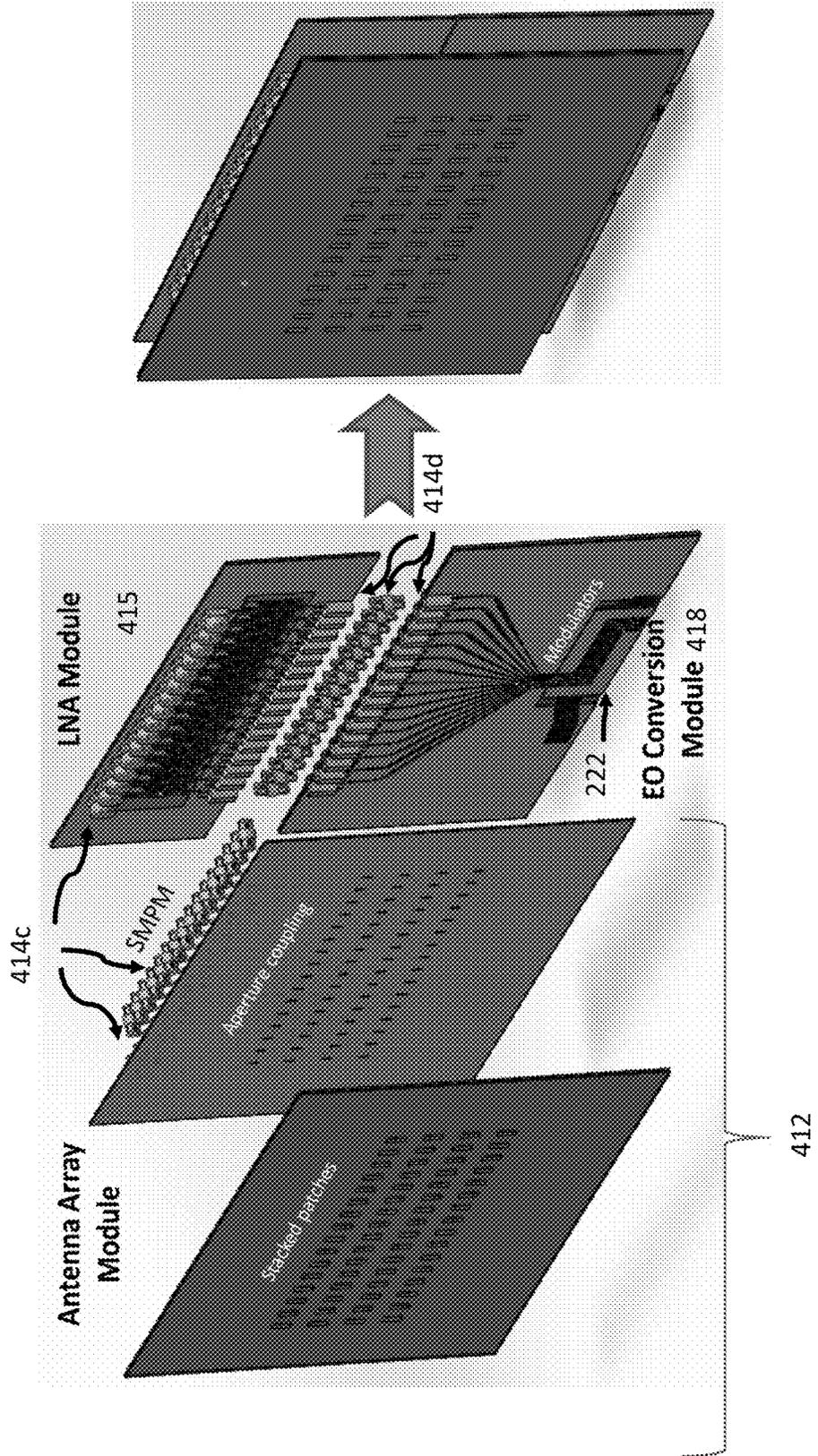


FIG. 5

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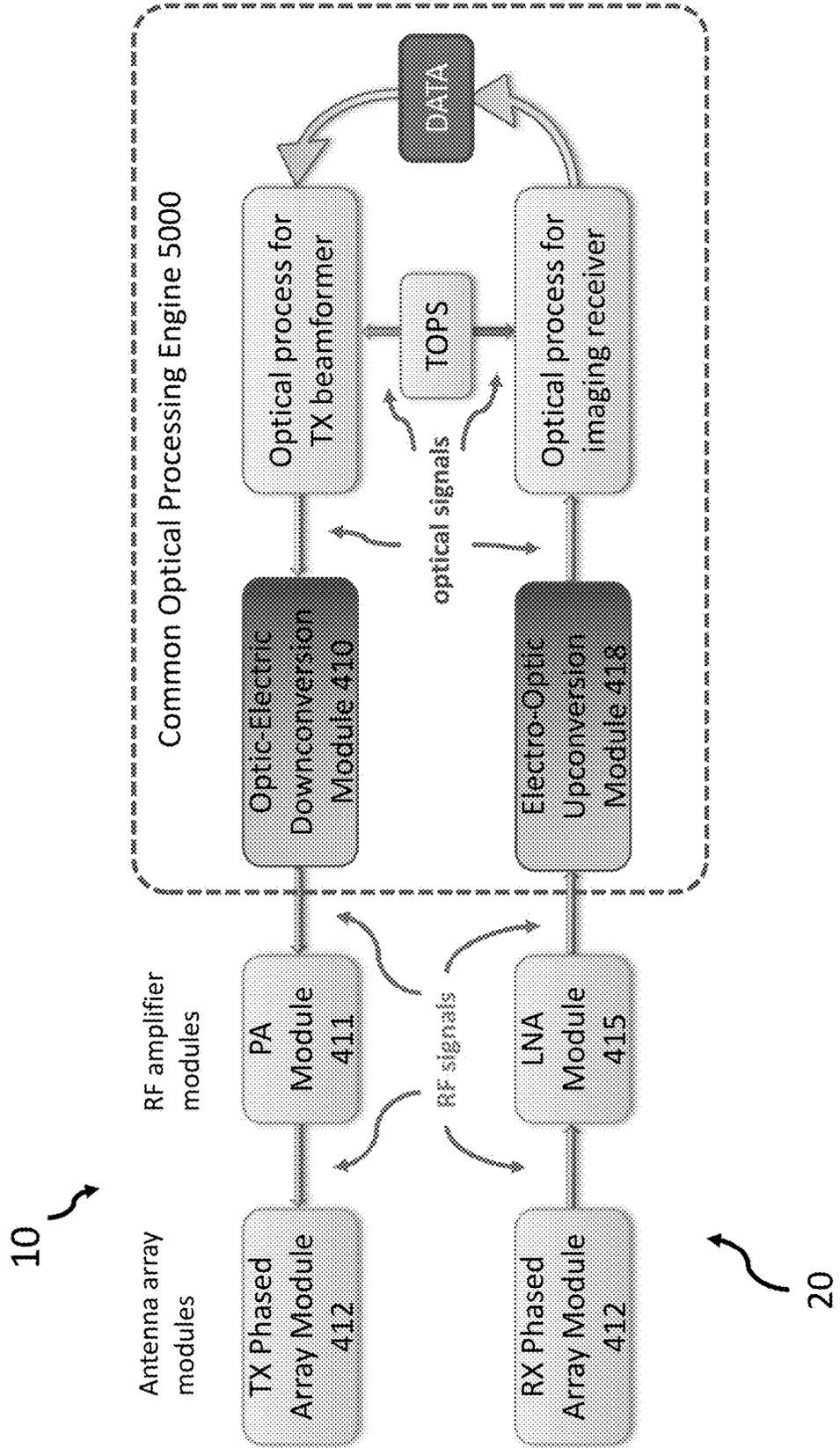


FIG. 6

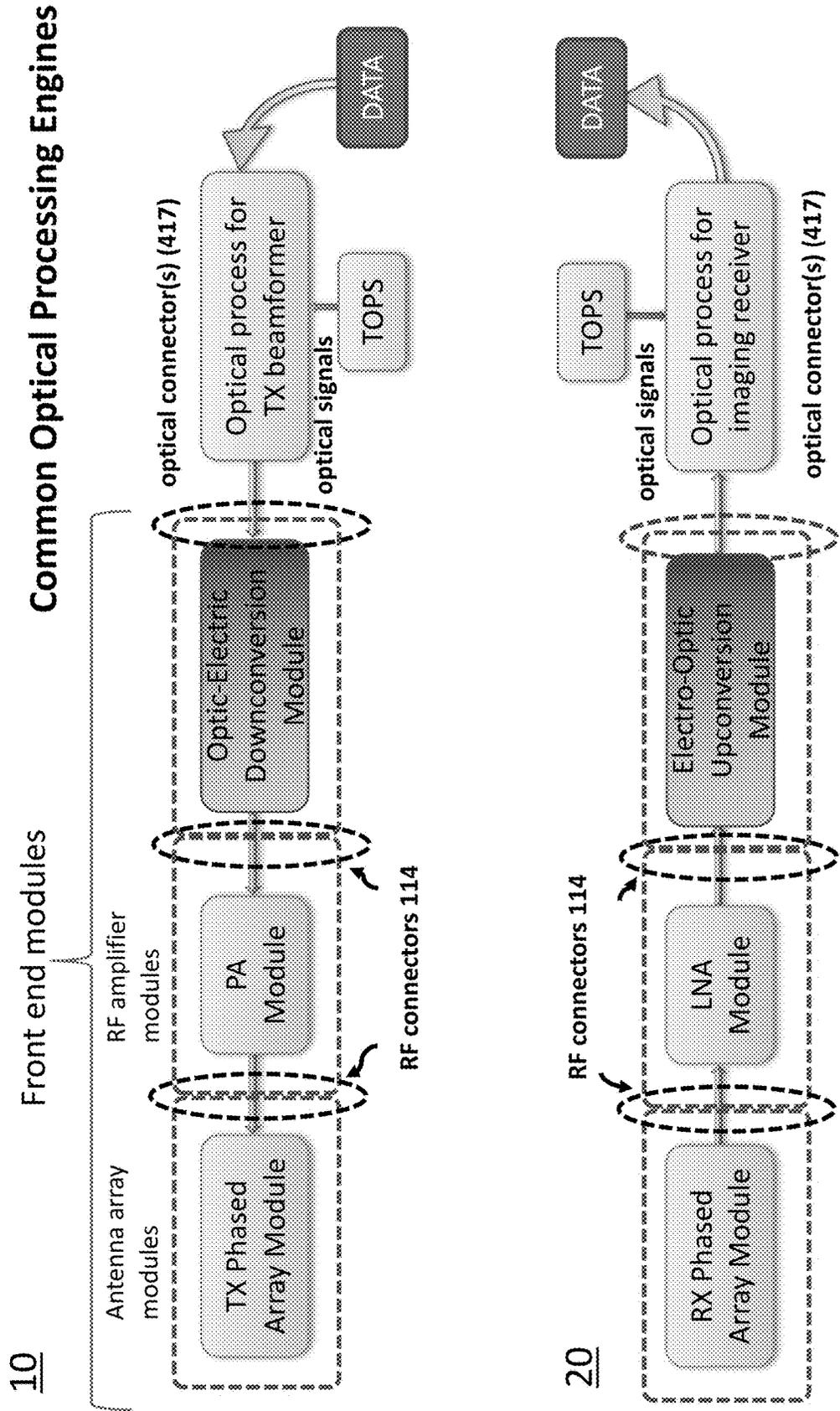


FIG. 7

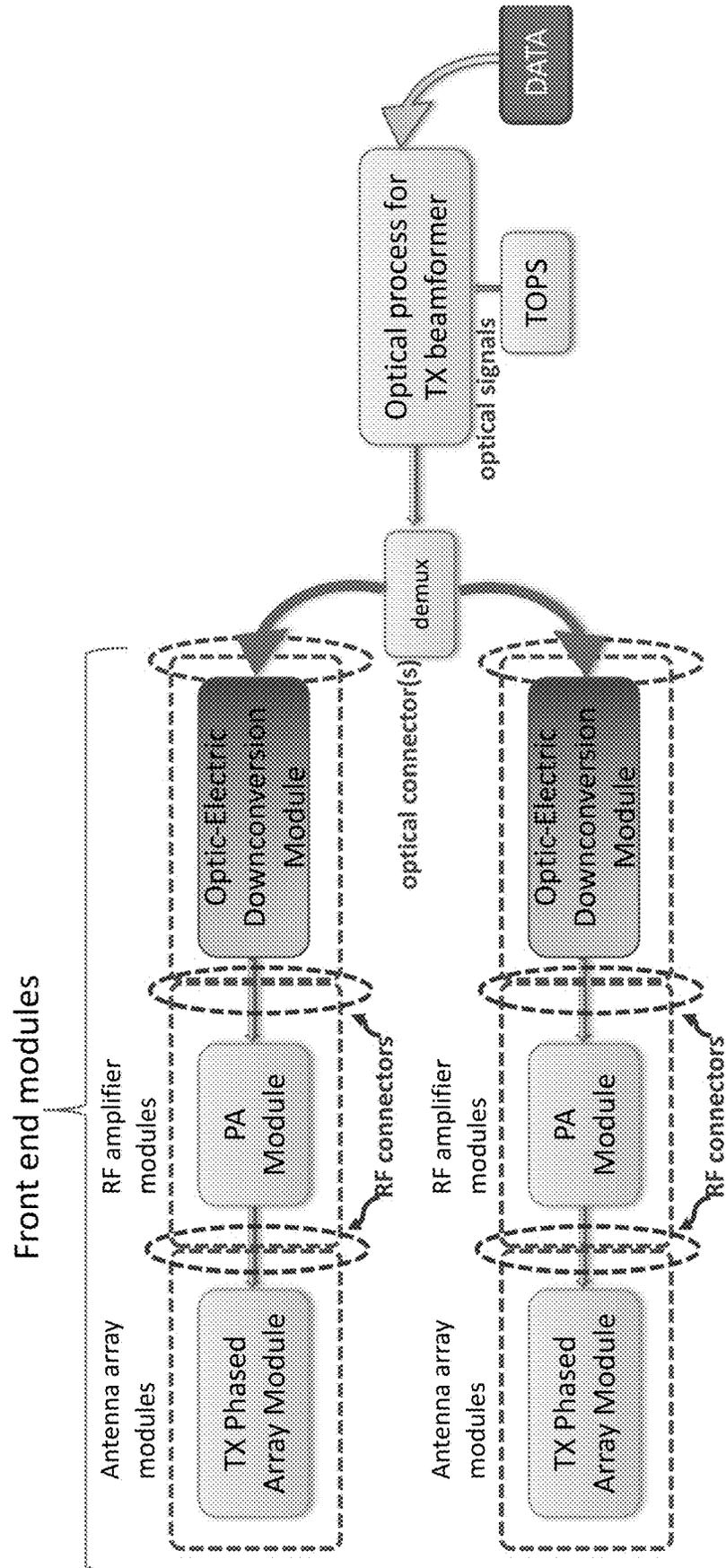


FIG. 8

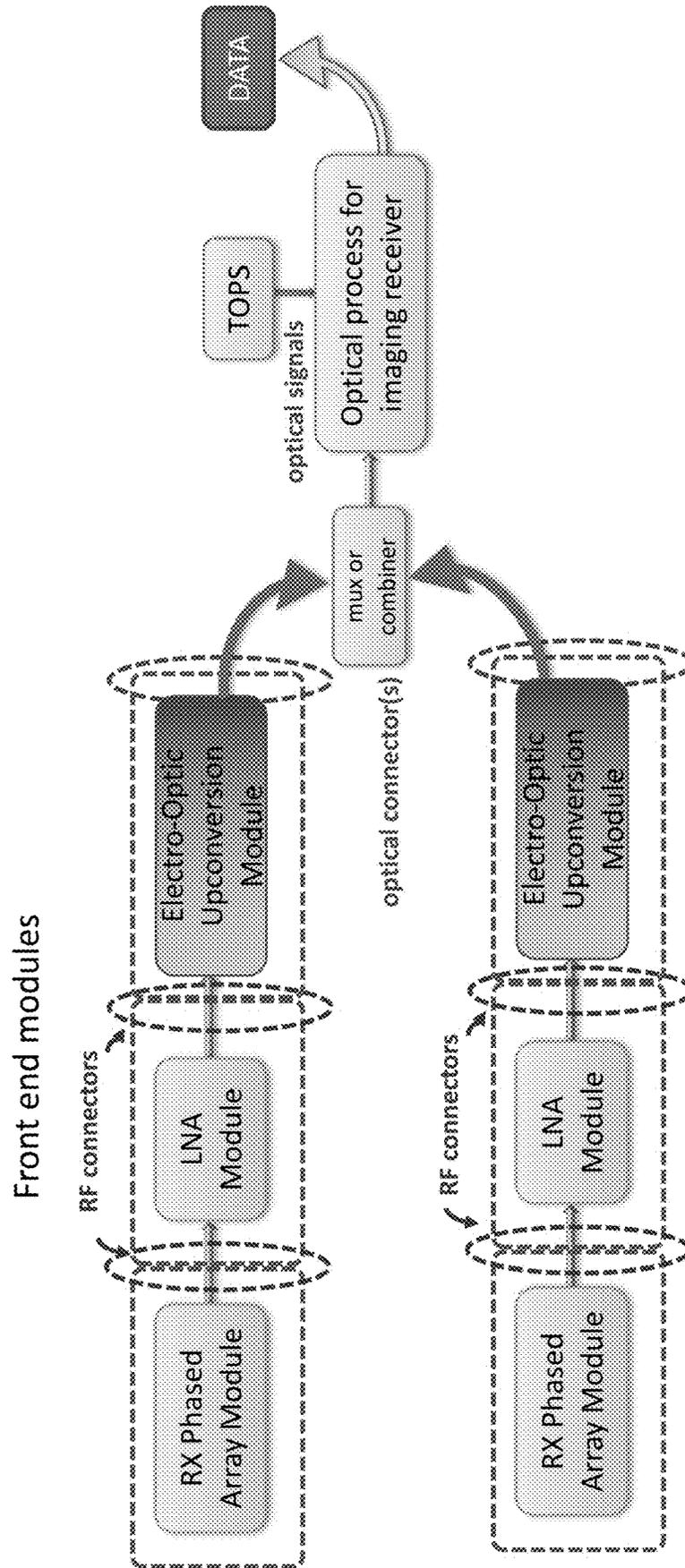
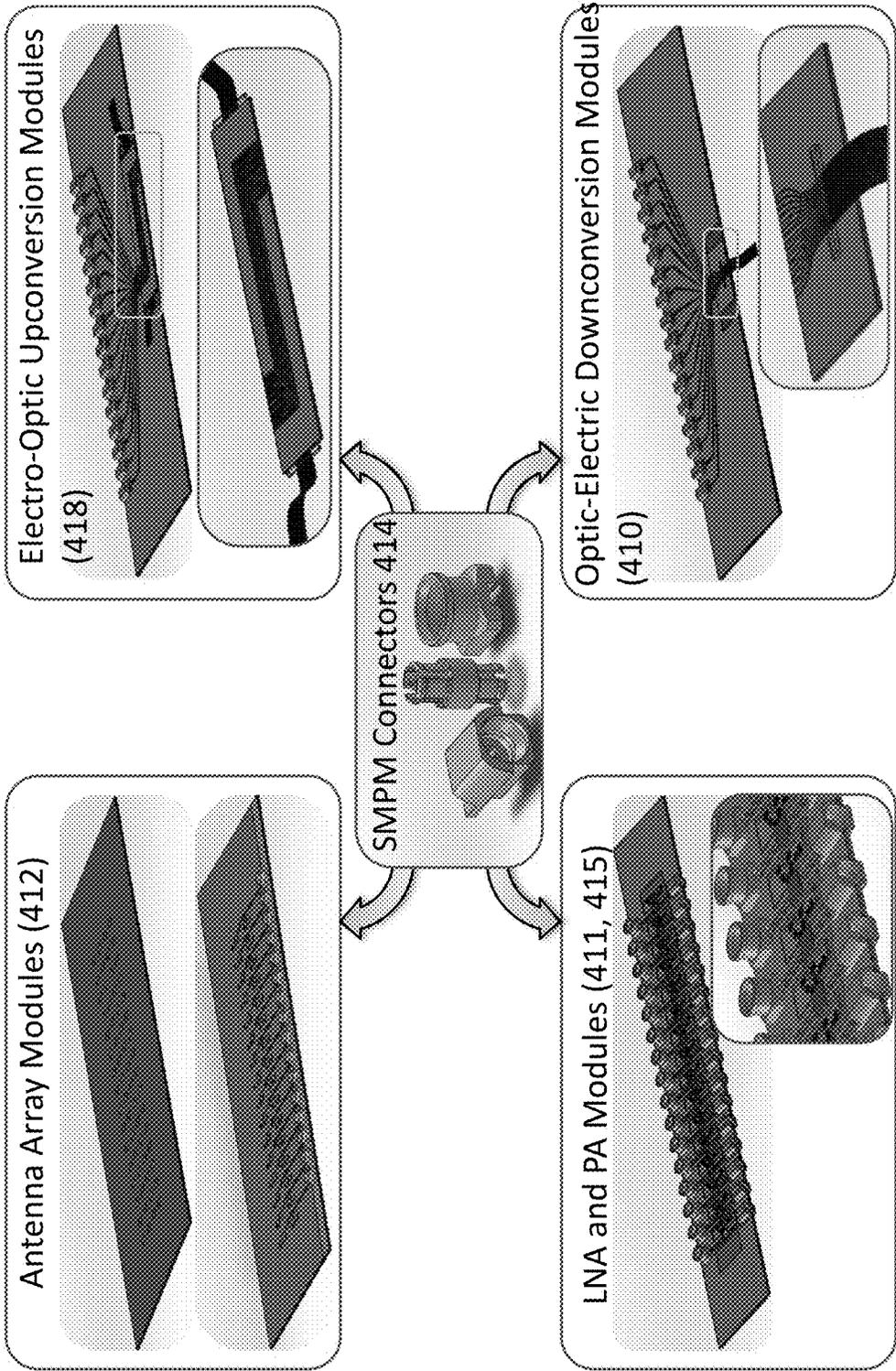


FIG. 9



## MODULAR ANTENNA SYSTEMS AND RELATED METHODS OF MANUFACTURE

### CROSS-REFERENCE TO RELATED APPLICATIONS

This application is a continuation of U.S. application Ser. No. 17/324,582, filed May 19, 2021, which is continuation of U.S. application Ser. No. 16/198,670, filed Nov. 21, 2018, which is a non-provisional application and claims priority to U.S. Provisional Application No. 62/589,534, filed Nov. 21, 2017 and U.S. Provisional Application No. 62/590,066, filed Nov. 22, 2017, the contents of each of which being incorporated by reference in their entirety.

### TECHNICAL FIELD

Example embodiments of the present disclosure relate to a novel antenna systems that may be formed in a modular fashion. The antenna systems may include antenna arrays that employ electro-optical converters as elements of a receiver and/or transmitter.

### BACKGROUND

Conformal, low profile, and wideband phased antenna arrays have received increasing attention due to their potential to provide multiple functionalities over several octaves of frequency, using shared common apertures for various applications, such as radar and communications.

### SUMMARY

Disclosed herein is a swappable modular-based radiofrequency (RF) frontend that may be used in configuring various transmitting (TX) and receiving (RX) phased array antenna systems for diverse applications. Such swappable RF frontend may be used with unique spatial and spectral optical processing of complex RF signals over an ultra-wide frequency band using an optically upconverted imaging receiver and optically addressed transmitting phased array technologies.

Methods of related operations and of manufacturing antenna systems are also disclosed. Other novel improvements disclosed herein may be appreciated from the following detailed disclosure.

### BRIEF DESCRIPTION OF DRAWINGS

The above and other aspects and features are reflected in the exemplary embodiments set forth herein, with reference to the accompanying figures in which:

FIGS. 1 to 5 illustrate a one embodiment with FIGS. 1 and 2 illustrating exemplary details of a transmitter, FIGS. 3 and 4 illustrating exemplary details of a receiver and FIG. 5 illustrating exemplary details of a transceiver that includes the receiver and receiver of FIGS. 1 to 4.

FIG. 6 illustrates an example where an opto-electrical downconversion module of the transmitter and the electro-optical upconversion module of the receiver are swappable.

FIGS. 7 and 8 respectively illustrate a transmitter and receiver that may switch between use of different front ends with a common optical processing engine.

FIG. 9 illustrates a kit and related method of manufacturing according to certain embodiments.

### DETAILED DESCRIPTION

The present disclosure now will be described more fully hereinafter with reference to the accompanying drawings, in

which various exemplary embodiments are shown. The invention may, however, be embodied in many different forms and should not be construed as limited to the exemplary embodiments set forth herein. These example exemplary embodiments are just that—examples—and many embodiments and variations are possible that do not require the details provided herein. It should also be emphasized that the disclosure provides details of alternative examples, but such listing of alternatives is not exhaustive. Furthermore, any consistency of detail between various exemplary embodiments should not be interpreted as requiring such detail—it is impracticable to list every possible variation for every feature described herein. The language of the claims should be referenced in determining the requirements of the invention.

Ordinal numbers such as “first,” “second,” “third,” etc. may be used simply as labels of certain elements, steps, etc., to distinguish such elements, steps, etc. from one another. Terms that are not described using “first,” “second,” etc., in the specification, may still be referred to as “first” or “second” in a claim. In addition, a term that is referenced with a particular ordinal number (e.g., “first” in a particular claim) may be described elsewhere with a different ordinal number (e.g., “second” in the specification or another claim).

It will be understood that when an element is referred to as being “connected” or “coupled” to or “on” another element, it can be directly connected or coupled to or on the other element or intervening elements may be present. In contrast, when an element is referred to as being “directly connected” or “directly coupled” to another element, or as “contacting” or “in contact with” another element, there are no intervening elements present.

As used herein, components described as being “electrically connected” are configured such that an electrical signal can be transferred from one component to the other (although such electrical signal may be attenuated in strength as it transferred). Moreover, components that are “directly electrically connected” share a common electrical node through electrical connections by one or more conductors, such as, for example, wires, pads, internal electrical lines, through vias, etc. As such, directly electrically connected components do not include components electrically connected through active elements, such as transistors or diodes.

Spatially relative terms, such as “beneath,” “below,” “lower,” “above,” “upper” and the like, may be used herein for ease of description to describe positional relationships, such as illustrated in the figures, e.g. It will be understood that the spatially relative terms encompass different orientations of the device in addition to the orientation depicted in the figures.

Terms such as “same,” “equal,” “planar,” or “coplanar,” as used herein encompass near identity including variations that may occur, for example, due to manufacturing processes. The term “substantially” may be used herein to emphasize this meaning, unless the context or other statements indicate otherwise.

Disclosed herein is a swappable modular-based radiofrequency (RF) frontend that may be used in configuring various transmitting (TX) and receiving (RX) phased array antenna systems for diverse applications. Such swappable RF frontend may be used with unique spatial and spectral optical processing of complex RF signals over an ultra-wide frequency band using an optically upconverted imaging receiver and/or optically addressed transmitting phased array technologies. Antenna systems implementing the swappable modular-based radiofrequency (RF) frontend

include antenna transmitters, antenna receivers and antenna transceivers. Exemplary details disclosed in connection with the antenna transmitters and antenna receivers will be understood to equally apply to the transmitting portion and receiving portion, respectively, of transceivers embodiments, and vice versa.

FIGS. 1 to 5 illustrate an exemplary embodiment of the invention. FIG. 1 illustrates an antenna transmitter 10 including a common TX optical processing engine 3000, an RF amplifier module 411a and an antenna array module 412a. The common optical processing engine 3000 is detachably connected to the RF amplifier module 411a by a first set of RF connectors 414. The RF amplifier module 411a is detachably connected to the RF antenna array module 412a by a second set of RF connectors 414. Thus, the common TX optical processing engine 3000, in communication with the RF antenna array module 412a via the RF amplifier module 411a, may operate to control the RF antenna array module 412a.

The common TX optical processing engine 3000 includes a channel encoder 300 that provides data to optical processor 2000. Optical processor 2000 may include an array of electro-optical modulators to combine and modulate phase and/or amplitude of light beams pairs provided from a tunable optical paired source TOPS module 1000 and provide the modulated combined light beams to the optic-electric downconversion module 410. The optic-electric downconversion module 410 may comprise an array of photodiodes that are driven by the modulated combined light beams output by optical processor 2000 to provide a corresponding RF electrical signal that is used to control a corresponding antenna element of the antenna array module 412. Prior to providing the RF electrical signals to the antenna elements of the antenna array module 412a, the RF electrical signals may be amplified by corresponding power amplifiers PA of the RF amplifier module 411a. In some examples, the RF amplifier module 411a may be omitted and the common TX optical processing engine 3000 may be directly connected to the antenna array module 412a with RF connectors 414. Further details of exemplary antenna transmitters 10 and their operation (including controlling/altering an RF frequency by controlling/altering a frequency difference of optical beam pairs) may be found in U.S. Provisional Application No. 62/590,066 filed Nov. 22, 2017, U.S. patent application Ser. No. 15/410,761 filed Jan. 19, 2017, U.S. patent application Ser. No. 15/242,459 filed Aug. 19, 2016, and U.S. patent application Ser. No. 16/198,652, filed Nov. 21, 2018 concurrently with the present application, the contents of each of these applications being incorporated by reference.

Also shown in FIG. 1 are several phased array modules 412 and several RF amplifier modules 411 that are unconnected to the common TX optical processing engine 3000. However, all of the phased array modules 412 and several RF amplifier modules 411 may be connected to and operated by the common TX optical processing engine 3000. The common TX optical processing engine 3000, the phased array modules 412 and the RF amplifier modules 411 are designed to be connected together in a modular fashion. The phased array module 412a and the RF amplifier module 411a, may be detachably connected to the common TX optical processing engine 3000 and may be swapped with other ones of the phased array modules 412 and several RF amplifier modules 411.

The common TX optical processing engine 3000 may provide RF signals to a connected antenna array module 412 in the form of an RF beat frequency resulting from the

interference of pairs of light beams. Each of the pairs of light beams may have frequencies that differ by an RF carrier frequency that is optimized for the antenna array module 412. The RF carrier frequency may correspond to an RF reference signal (not shown) provided to the TOPS module 1000. Thus, by modifying the RF reference signal provided to the TOPS module 1000, the RF beat frequency provided to the antenna array module (in the form of interfering light beams) may be modified without requiring modification of the transmission system (e.g., optical fibers) providing the RF beat frequency to the antenna array module 412.

The common TX optical processing engine 3000, the phased array modules 412 and the RF amplifier modules 411 may be connected together in a modular fashion. Each of the RF amplifier modules 411 may have an identical input RF connector that may mate with an output RF connector of the common TX optical processing engine 3000. For example, each input RF connector of the amplifier modules 411 may comprise the same number and layout of individual RF connectors that correspond in location and layout (e.g., in a mirror image fashion) to individual output RF connectors of the optical processing engine 3000. In one example, the input RF connector of a selected amplifier module 411 may be connected to the output RF connector of the common TX optical processing engine 3000 via miniaturized SMP (SMPM) connectors (a subminiature push-on, micro connector), for board-to-board connection.

Similarly, each of the RF amplifier modules 411 may have an identical output RF connector and each of the RF antenna array modules 412 may have an identical input RF connector. The output RF connectors of the amplifier modules 411 may comprise the same number and layout of individual RF connectors that correspond in location and layout (e.g., in a mirror image fashion) to individual input RF connectors of each of RF antenna array modules 412. In one example, the output RF connector of a selected amplifier module 411 may be connected to the input RF connector of a selected RF antenna array modules 412 via miniaturized SMP (SMPM) connectors (a subminiature push-on, micro connector), for board-to-board connection.

In assembling and/or manufacturing the antenna transmitter 10, a manufacturer, user, customer, etc. may select a desired antenna array module 412 and an RF amplifier module 411, such as based on desired RF frequency transmissions. The selected RF amplifier module 411 may be plugged into the common TX optical processing engine 3000 via the RF connectors described herein and the selected antenna array module 412 may be plugged into the selected amplifier module 411. Such connections between the common TX optical processing engine 3000, the RF amplifier module 411 and the phased array module 412 may be performed so that all individual RF connections between the two corresponding RF connectors may be made at the same time (e.g., by simply pressing the two corresponding RF connectors together to mate all individual RF connections at the same time). The connected modules 411, 412 may be separated from each other with similar ease. Although the modules 411, 412 and the optical processing engine 3000 may have their corresponding RF connectors removably connected to one another (which may be sufficient for providing both electrical and physical connections therebetween), additional physical connectors may be desired (e.g., clamps between the different modules) to strengthen the physical connections.

As part of assembling the antenna transmitter 10, in response to the selection of the antenna array module 412 and amplifier module 411, the optical processing engine

**3000** may be configured in response thereto. For example, the optical processing engine **3000** may receive a mode selection from a user or otherwise be programmed corresponding to the selection of the antenna array module **412** and amplifier module **411**. The mode selection may configure the optical processing engine **3000** to control the selected antenna array module **412** to operate at a RF carrier frequency (or RF carrier frequency band) corresponding to the selected antenna array module **412** and/or amplifier module **411**. For example, the optical processing engine **3000** may be put in a first mode to operate antenna array module **412a** with a RF carrier frequency of 5 GHz (or at a RF carrier frequency band centered about or including 5 GHz), which may correspond to an optimal operational frequency of the antenna array module **412a** (e.g., antenna radiating elements of the antenna array module **412a** may have a length of one half of a wavelength of electromagnetic radiation corresponding to the RF carrier frequency of 5 GHz).

If a different antenna array module **412** and amplifier module **411** are later selected corresponding to a different RF carrier frequency (e.g., one of 28 GHz, 38 GHz or 64 GHz in this example), the optical processing engine **3000** may be put into a different mode corresponding to this selection, e.g., by a mode selection input by a user or by reprogramming by a user (user interface to receive user mode selection or reprogramming of common TX optical processing engine **3000** not shown in FIG. 1). The mode selection may cause the RF reference signal provided to the TOPS module **1000** to change frequency to alter the wavelength offset (or wavelength differences) between the optical beam pair(s) provided by the TOPS module **1000**. The resulting RF signals provided in the form of a beat frequency of interfering light beams may thus be altered in a simple manner.

As another example, the mode selection by a user corresponding to the selection of the antenna array module **412** and amplifier module **411** may cause modification of calibration data used by the optical processing engine **3000**, such as calibration values used to calibrate phases RF signals provided by the optical processing engine **3000** (provided as beat frequencies as discussed elsewhere herein). Calibration of the phases of the RF signals provided by the optical processing engine **3000** may cause these RF signals to be in phase absent any modulation responsive to encoder **300**.

Thus, the transmitter **10** provides a common TX optical processing engine **3000** that may be used with antenna array module **412** and amplifier module **411** that are designed for different operating frequencies (i.e., different RF carrier frequencies/frequency bands). It will be appreciated that operation of the different antenna array modules **412** and amplifier modules **411** may not be optimum (or even operable) if provided with RF signals of frequencies intended for other antenna array modules **412** and amplifier modules **411**. However, the common TX optical processing engine **3000** is configurable to easily change the RF signal frequencies provided to the antenna array modules **412** and amplifier modules **411** via mode selection or reprogramming.

FIG. 2 illustrates exemplary details of the physical features of an antenna transmitter **10** according to one embodiment. The left side of FIG. 2 illustrates an exploded view of the element of antenna transmitter and is representative of the structure of this antenna transmitter **10** prior to assembly. The right side of FIG. 2 illustrates the configuration of the antenna transmitter **10** after assembly. As will be appreciated, the assembled antenna transmitter **10** has a low profile, which can have a thickness of less than 20 mm, such as 10

mm or less, e.g. RF connectors **414a** connect antenna array module **412** to power amplifier module **411** and RF connectors **414b** connect power amplifier module **411** to the opto-electric conversion module **410** of the common TX optical processing engine **3000**. The opto-electric conversion module **410** may be connected to the remainder of the TX optical processing engine **3000** via optical fibers.

In this example, RF connectors **414a** of the antenna array module **412** and power amplifier module **411** are both female connectors connected together with SMPM RF connectors (plug type). Each of these female RF connectors **414a** has the individual RF connectors (forming the larger female RF connector) aligned and extending perpendicular from the planar substrate (which may be a printed circuit board) of the corresponding module **411**, **412**. Each of these female RF connectors **414a** of modules **411**, **412** may be fixed to the substrate of the module **411**, **412** so that the individual RF connectors forming the larger female RF connector **414a** maintain a fixed positional relationship (e.g., linearly arrayed and having connecting ends terminating at the same plane).

RF connectors **414b** of the power amplifier module **411** and the opto-electric conversion module **410** in this example are also female connectors connected by SMPM RF connectors. Each of these female RF connectors **414b** has the individual RF connectors (forming the larger female RF connector) aligned and extending parallel to the planar substrate and along an edge of the planar substrate of the corresponding module **410**, **411**. Each of these female RF connectors **414b** of modules **410**, **411** may be fixed to the substrate of the corresponding module **410**, **411** so that the individual RF connectors forming the larger female RF connector **414b** maintain a fixed positional relationship (e.g., linearly arrayed and having connecting ends terminating at the same plane).

The receiving phased array (receiver) may be implemented as an imaging receiver, providing analog beam forming to all received RF signals that are upconverted to the optical domain using an analog process that preserves spatial coherence over the entire array. Ultrawideband electro-optic (EO) modulators are components in this optical processor. See, for example, U.S. patent application Ser. No. 14/791,351 filed Jul. 3, 2015 and issued as U.S. Pat. No. 9,525,489 on Dec. 20, 2016, incorporated by reference in its entirety, showing exemplary details of an imaging receiver, including exemplary antenna arrays, an optical processing engine (an optical processor) and the components therebetween. Other receiving phased arrays may be implemented, such as that described in U.S. Pat. No. 15,227,859 filed Aug. 3, 2016, the contents of which are hereby incorporated by reference.

FIG. 3 illustrates an antenna receiver **20** including a common RX optical processing engine **4000**, an RF amplifier module **415a** and an antenna array module **412a**. The common optical processing engine **4000** is detachably connected to the RF amplifier module **415a** by a first set of RF connectors **414**. The RF amplifier module **415a** is detachably connected to the RF antenna array module **412a** by a second set of RF connectors **414**. Thus, the common RX optical processing engine **4000**, in communication with the RF antenna array module **412a** via the RF amplifier module **415a**, may operate to receive and process RF signals received by the RF antenna array module **412a**. For example, after RF signals received by the antenna array module **412a** is amplified by the RF amplifier module **415a**, an electro-optic upconversion module **418** of the common RX optical processing engine **4000** may upconvert the RF signals to

corresponding light signals via modulation which may be used, e.g., to extract an image of an RF scene. RF sources of the RF scene may be identified and encoded data may be extracted by the optical processor of the imaging receiver **5000**.

Like the transmitter **10** described with respect to FIGS. **1** and **2**, the common optical processing engine **4000** may operate with different RF antenna array modules **412** and different RF amplifier modules **415**. The different modules **412**, **415** may be swappable and with detachable connections as described with respect to transmitter **10** and a repetitive description is not repeated here.

It should be appreciated that the same RF antenna array modules **412** may be selected for use with either the transmitter **10** or the receiver **20**. To facilitate such use, connectors of the amplifier modules **411** and **415** that mate with the RF antenna array modules **412** may be identical with each other. However, other implementations may select from different sets of RF antenna array modules for assembling a transmitter **10** or a receiver **20**.

FIG. **4** illustrates exemplary details of the physical features of an antenna receiver **20** according to one embodiment. The left side of FIG. **4** illustrates an exploded view of the element of antenna receiver **20** and is representative of the structure of this antenna receiver **20** prior to assembly. The right side of FIG. **2** illustrates the configuration of the antenna receiver **20** after assembly. As will be appreciated, the assembled antenna receiver **20** has a low profile, which can have a thickness of less than 20 mm, such as 10 mm or less, e.g. RF connectors **414c** connect antenna array module **412** to low noise amplifier module **415** and RF connectors **414d** connect low noise amplifier module **415** to the electro-optic conversion module of the common RX optical processing engine **4000**. The electro-optic conversion module may be connected to the remainder of the RX optical processing engine **4000** via optical fibers. RF connectors **414c** and **414d** may have a similar configuration, be similarly connected to the substrates of the corresponding modules **412**, **415** and similarly connect the modules **412**, **415** in the same way as described with respect to connectors **414a**, **414b** of the antenna transmitter **10** and a repetitive description is omitted here.

FIG. **5** illustrates an example where the transmitter **10** of FIG. **1** and the receiver **20** of FIG. **3** are combined as part of a single transceiver **30**. Structure and operation of the transmitter and receiver **20** may be the same as that described herein. Note that the DATA illustrated in FIG. **5** may be different from what is extracted via the receiver **20** and what is transmitted by the transmitter **10**.

The EO upconversion module, the OE downconversion module, and/or the optical-based backend processor may be provided as a common optical processing engine in both TX and RX phased arrays such that it may be used with different antenna arrays having different RF personalities. As disclosed herein, an optical processing engine may allow the backend processor to integrate different RF frontend modules with respective RF personalities, such having different frequency bandwidths, radiation power, gain, and beam steering characteristics. A variety of RF phased array modules can be developed to meet the desired requirement. To improve the signal fidelity, a low noise amplifier (LNA) and power amplifier (PA) modules are incorporated into TX and RX systems. In some examples, low noise amplifier (LNA) and power amplifier (PA) modules need not be implemented and antenna array modules may directly connect to the optical processing engine, and/or more directly connect to an EO upconversion module or the OE downconversion

module as appropriate. As with the remaining portions of the optical processing engine, each EO upconversion module and each OE downconversion module may operate with different antenna arrays that are operable at different frequencies, such as those frequencies described herein.

Each RF module may be built on high-frequency substrates. The RF connection between different RF modules can be realized via advanced RF connectors, i.e., miniaturized SMP (SMPM) connectors (a subminiature push-on, micro connector), for board-to-board connection. SMPM are designed for direct snap-on connection over a frequency up to 67 GHz with a minimal insertion loss. The connectors is able to self-align to withstand radial and axial misalignment inherent with board-to-board mating. In addition, smaller feature, <30% of SMP designs, enables dense integration of a high frequency phased array.

The convenient interconnect using the SMPM adaptor array between the common optical engine and RF frontend module allows easy swapping and use of different RF frontends with the same optical processing engine by choosing different RF phased array, LNA and PA modules that are suitable to a designated application.

In some examples, other elements of the receiver, transmitter and transceiver may be made modular and be swappable as described with respect to the antenna array modules and the RF amplifier modules **411**, **415**. FIG. **6** illustrates an example where the opto-electrical downconversion module of the transmitter **10** and the electro-optical upconversion module **418** of the receiver **20** are removably attached to the remaining portions of the corresponding common optical processing engine (via mated optical connectors) and to a corresponding amplifier module (via mated RF connectors). Such alternative configuration may be provided as part of the transmitter **10**, receiver **20** or transceiver **30** described herein.

In some examples, switching front end modules need not result in physical replacement. FIG. **7** illustrates an example of a receiver using a common optical processing engine that may switch between different TX antenna array modules. Switching between the different TX antenna array modules may be implemented by switches, such as an optical demultiplexer that may be controlled to select which of several front end modules should be used for RF transmission. Two switchable antenna array modules are shown in FIG. **7**, but the number may be significantly more than two (e.g., 5 or more). Each of the front end modules (and different antenna array modules) may be configured to operate at a different RF carrier frequency band. Remaining features of the transmitter **10** of FIG. **7** may be the same as described elsewhere herein. FIG. **8** illustrates an example of a RX antenna array that may use a common optical processing engine that may switch between different front end modules by use of a demultiplexer. Alternatively, several front end modules may have optical signals (corresponding to the RF signals obtained from different antenna arrays combined and processed simultaneously by the optical processing engine. Digital filtering may be used in this instance if desired.

In some examples, the invention may be provided in the form of a kit. In the exemplary embodiment of FIG. **9**, a kit may comprise one or more of the common optical processing engines described herein (not shown in FIG. **9**) (such as **3000**, **4000** and **5000**), one or a plurality of antenna array modules (**412**), LNA and PA Modules (**411**, **415**), optoelectric downconversion modules (**410**) and/or electro-optic upconversion modules (**418**). The optical processing engines (**3000**, **4000**, **5000**) and modules (**410**, **411**, **412**, **415** and **418**) may be detachably connectable and thus swappable as

described herein. In some examples, a transmitter **10**, receiver **20** and/or a transceiver **30** may be manufactured by assembling the appropriate optical processing engine and modules, such as described elsewhere herein.

It is emphasized that the descriptions herein are exemplary and deviations from which will be recognized to fall within the scope of the invention as set forth in the claims of this application.

What is claimed is:

**1.** A modular radio frequency (RF) transmitter comprising:

an optical processor including a plurality of electro-optical modulators to provide a plurality of combined modulated light beam pairs, each light beam pair being modulated in at least one of phase and amplitude;

an optical connector connected to the optical processor; a plurality of first sets of RF connectors; and

a plurality of front end modules each detachably connected to the optical connector via a corresponding first set of RF connectors, each of the plurality of front end modules comprising plural component modules including

an opto-electrical downconversion module including a plurality of photodiodes, each photodiode being driven by a corresponding light beam pair to provide a corresponding RF electrical signal, and

an RF antenna array module comprising a plurality of antenna elements each in communication with a corresponding photodiode to receive the corresponding RF electrical signal provided by the photodiode via a corresponding one of the RF connectors to control the antenna element.

**2.** The modular RF transmitter of claim **1**, wherein the optical connector is an optical demultiplexer.

**3.** The modular RF transmitter of claim **1**, wherein the component modules of each of the plurality of front end modules further include an RF amplifier module including a plurality of amplifiers, wherein the RF amplifier module is in communication with a corresponding opto-electrical downconversion module to receive the RF electrical signals provided by the photodiodes and amplify the RF electrical signals with corresponding ones of the amplifiers, and wherein the RF amplifier module is in communication with a corresponding RF antenna array module to provide the amplified RF electrical signals to the antenna elements of the corresponding RF antenna array module.

**4.** The modular RF transmitter of claim **3**, wherein the RF amplifier module is detachably connected to the corresponding opto-electrical downconversion module via a second set of RF connectors.

**5.** The modular RF transmitter of claim **3**, wherein the RF amplifier module is detachably connected to the corresponding RF antenna array module via a third set of RF connectors.

**6.** The modular RF transmitter of claim **1**, wherein each antenna element of the RF antenna array module is directly electrically connected to a corresponding one of the photodiodes of the opto-electrical downconversion module via a second set of the RF connectors.

**7.** The modular RF transmitter of claim **1**, wherein the opto-electrical downconversion module and the RF antenna array module are formed on corresponding substrates that are detachably connected together via a second set of RF connectors.

**8.** The modular RF transmitter of claim **7**, wherein each of the substrates of the opto-electrical downconversion module and the RF antenna array module is a printed circuit board.

**9.** The modular RF transmitter of claim **1**,

wherein the component modules of each of the plurality of front end modules further include an RF amplifier module including a plurality of amplifiers, wherein the RF amplifier module is in communication with a corresponding opto-electrical downconversion module to receive the RF electrical signals provided by the photodiodes and amplify the RF electrical signals with corresponding ones of the amplifiers, and wherein the RF amplifier module is in communication with a corresponding RF antenna array module to provide the amplified RF electrical signals to the antenna elements of the corresponding RF antenna array module, and

wherein the corresponding opto-electrical downconversion module and the RF amplifier module are formed on corresponding substrates that are detachably connected together via a second set of RF connectors.

**10.** The modular RF transmitter of claim **9**, wherein the corresponding RF antenna array module is formed on a substrate that is detachably connected to the substrate of the RF amplifier module via a third set of RF connectors.

**11.** The modular RF transmitter of claim **10**, wherein each of the substrates of the opto-electrical downconversion module, the RF amplifier module and the RF antenna array module is a printed circuit board.

**12.** The modular RF transmitter of claim **1**, wherein each of the plurality of front end modules are configured to operate at different RF carrier frequencies.

**13.** The modular RF transmitter of claim **12**, wherein the different RF carrier frequencies include at least two of 5 GHz, 28 GHz, 38 GHz, and 64 GHz.

**14.** The modular RF transmitter of claim **1**, wherein the optical processor comprises an input to receive a mode selection to put the optical processor into a mode corresponding to a selected RF carrier frequency.

**15.** The modular RF transmitter of claim **1**,

wherein the first sets of RF connectors are each formed of the same number of RF connectors and arranged in the same layout.

**16.** The modular RF transmitter of claim **1**, wherein the first set of RF connectors are subminiature push-on micro (SMPM) connectors.

**17.** The modular RF transmitter of claim **1**, wherein each of the front end modules has a thickness of less than 20 mm.

**18.** The modular RF transmitter of claim **1**, wherein the component modules of the front end modules are connected to each other via a corresponding snap-on connection.

**19.** The modular RF transmitter of claim **1**, wherein each of the component modules of each front end module are formed on a corresponding planar substrate that is removably connected to other component modules of the corresponding front end module.

**20.** The modular RF transmitter of claim **19**, wherein the planar substrates of each front end module are removably connected to each other to form a corresponding stack.

**21.** The modular RF transmitter of claim **20**, wherein each front end module has a thickness of less than 20 mm.

**22.** The modular RF transmitter of claim **19**, wherein each of the component modules of each front end module are removably connected to other component modules of the corresponding front end module via one or more second sets of RF connectors.

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23. The modular RF transmitter of claim 22, wherein the one or more second sets of RF connectors of the front end modules have an operating frequency of up to 67 GHz.

24. A modular radio frequency (RF) receiver comprising:  
a plurality of a first sets of RF connectors;

an optical connector;

a plurality of front end modules each detachably connected to the optical connector via a corresponding first set of RF connectors, each of the plurality of front end modules comprising plural component modules including

an RF antenna array module including a plurality of antenna elements, and

an electro-optical upconversion module detachably connected to the optical connector via the corresponding first set of RF connectors, the electro-optical upconversion module comprising a plurality of electro-optic modulators, each configured to receive a corresponding RF electrical signal from a corresponding one of the antenna elements of the RF antenna array via a corresponding second set of RF connectors to provide a corresponding optical signal; and

an optical processor connected to the optical connector and configured to extract encoded data from the optical signals provided by the electro-optic modulators of the electro-optical upconversion module.

25. The modular RF receiver of claim 24, wherein the optical connector is an optical multiplexer.

26. The modular RF receiver of claim 24, wherein the component modules of each of the plurality of front end modules further include an RF amplifier module including a plurality of amplifiers, wherein the RF amplifier module is in communication with a corresponding RF antenna array module to receive the RF electrical signals provided by the antenna elements of the RF antenna array module, and amplify the RF electrical signals with corresponding ones of the amplifiers, and wherein the RF amplifier module is in communication with a corresponding electro-optical upconversion module to provide the amplified RF electrical signals to electro-optic modulators of the corresponding electro-optical upconversion module.

27. The modular RF receiver of claim 26, wherein the RF amplifier module is detachably connected to the corresponding electro-optical upconversion module via a second set of RF connectors.

28. The modular RF receiver of claim 26, wherein the RF amplifier module is detachably connected to the corresponding RF antenna array module via a third set of RF connectors.

29. The modular RF receiver of claim 24, wherein each antenna element of the RF antenna array module is directly electrically connected to a corresponding one of the electro-optic modulators of the electro-optical upconversion module via a second set of the RF connectors.

30. The modular RF receiver of claim 24, wherein the electro-optical upconversion module and the RF antenna array module are formed on corresponding substrates that are detachably connected together via a second set of RF connectors.

31. The modular RF receiver of claim 30, wherein each of the substrates of the electro-optical upconversion module and the RF antenna array module is a printed circuit board.

32. The modular RF receiver of claim 24,

wherein the component modules of each of the plurality of front end modules further include an RF amplifier module including a plurality of amplifiers, wherein the

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RF amplifier module is in communication with a corresponding RF antenna array module to receive the RF electrical signals provided by the antenna elements of the RF antenna array module, and amplify the RF electrical signals with corresponding ones of the amplifiers, and wherein the RF amplifier module is in communication with a corresponding electro-optical upconversion module to provide the amplified RF electrical signals to electro-optic modulators of the corresponding electro-optical upconversion module, and

wherein the corresponding electro-optical upconversion module and the RF amplifier module are formed on corresponding substrates that are detachably connected together via a second set of RF connectors.

33. The modular RF receiver of claim 32, wherein the corresponding RF antenna array module is formed on a substrate that is detachably connected to the substrate of the RF amplifier module via a third set of RF connectors.

34. The modular RF receiver of claim 33, wherein each of the substrates of the electro-optical upconversion module, the RF amplifier module and the RF antenna array module is a printed circuit board.

35. The modular RF receiver of claim 34, wherein the optical processor comprises an input to receive a mode selection to put the optical processor into a mode corresponding to a selected RF carrier frequency.

36. The modular RF receiver of claim 24, wherein each of the plurality of front end modules are configured to operate at different RF carrier frequencies.

37. The modular RF receiver of claim 36, wherein the different RF carrier frequencies include at least two of 5 GHz, 28 GHz, 38 GHz, and 64 GHz.

38. The modular RF receiver of claim 24,

wherein the first sets of RF connectors are each formed of the same number of RF connectors and arranged in the same layout

wherein the number of input connectors is the same as the number of output connectors.

39. The modular RF receiver of claim 24, wherein the first sets of RF connectors are identical to each other.

40. The modular RF receiver of claim 24, wherein the first set of RF connectors are subminiature push-on micro (SMPM) connectors.

41. The modular RF receiver of claim 24, wherein each of the plurality of front end modules has a thickness of less than 20 mm.

42. The modular RF receiver of claim 24, wherein the component modules of the front end modules are connected to each other via a corresponding snap-on connection.

43. The modular RF receiver of claim 24, wherein each of the component modules of each front end module are formed on a corresponding planar substrate that is removably connected to other component modules of the corresponding front end module.

44. The modular RF receiver of claim 43, wherein the planar substrates of each front end module are removably connected to each other to form a corresponding stack.

45. The modular RF receiver of claim 44, wherein each front end module has a thickness of less than 20 mm.

46. The modular RF receiver of claim 43, wherein each of the component modules of each front end module are removably connected to other component modules of the corresponding front end module via one or more second sets of RF connectors.

47. The modular RF receiver of claim 46, wherein the one or more second sets of RF connectors of the front end modules have an operating frequency of up to 67 GHz.

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48. A modular radio frequency (RF) transmitter kit comprising:  
 an optical processor including a plurality of electro-optical modulators to provide a plurality of combined modulated light beam pairs, each light beam pair being modulated in at least one of phase and amplitude;  
 an optical connector being detachably connectable to the optical processor;  
 a plurality of first sets of RF connectors; and  
 a plurality of front end modules each being detachably connectable to the optical connector via a corresponding first set of RF connectors, each of the plurality of front end modules comprising plural component modules including  
 an opto-electrical downconversion module including a plurality of photodiodes, each photodiode being driven by a corresponding light beam pair to provide a corresponding RF electrical signal, and  
 an RF antenna array module comprising a plurality of antenna elements each in communication with a corresponding photodiode to receive the corresponding RF electrical signal provided by the photodiode via a corresponding one of the RF connectors to control the antenna element.
49. The modular RF transmitter kit of claim 48, wherein the optical connector is an optical demultiplexer.
50. The modular RF transmitter kit of claim 48, wherein the component modules of each of the plurality of front end modules further include an RF amplifier module including a plurality of amplifiers, wherein the RF amplifier module is in communication with a corresponding opto-electrical downconversion module to receive the RF electrical signals provided by the photodiodes and amplify the RF electrical signals with corresponding ones of the amplifiers, and wherein the RF amplifier module is in communication with a corresponding RF antenna array module to provide the amplified RF electrical signals to the antenna elements of the corresponding RF antenna array module.
51. The modular RF transmitter kit of claim 48, wherein the opto-electrical downconversion module and the RF antenna array module are formed on corresponding substrates that are detachably connected together via a second set of RF connectors.
52. The modular RF transmitter kit of claim 51, wherein each of the substrates of the opto-electrical downconversion module and the RF antenna array module is a printed circuit board.
53. A modular radio frequency (RF) receiver kit comprising:  
 a plurality of a first sets of RF connectors;

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- an optical connector;  
 a plurality of front end modules each being detachably connected to the optical connector via a corresponding first set of RF connectors, each of the plurality of front end modules comprising plural component modules including  
 an RF antenna array module including a plurality of antenna elements, and  
 an electro-optical upconversion module detachably connected to the optical connector via the corresponding first set of RF connectors, the electro-optical upconversion module comprising a plurality of electro-optic modulators, each configured to receive a corresponding RF electrical signal from a corresponding one of the antenna elements of the RF antenna array via a corresponding second set of RF connectors to provide a corresponding optical signal;  
 and  
 an optical processor being detachably connectable to the optical connector and configured to extract encoded data from the optical signals provided by the electro-optic modulators of the electro-optical upconversion module.
54. The modular RF receiver kit of claim 53, wherein the optical connector is an optical multiplexer.
55. The modular RF receiver kit of claim 53, wherein the component modules of each of the plurality of front end modules further include an RF amplifier module including a plurality of amplifiers, wherein the RF amplifier module is in communication with a corresponding RF antenna array module to receive the RF electrical signals provided by the antenna elements of the RF antenna array module, and amplify the RF electrical signals with corresponding ones of the amplifiers, and wherein the RF amplifier module is in communication with a corresponding electro-optical upconversion module to provide the amplified RF electrical signals to electro-optic modulators of the corresponding electro-optical upconversion module.
56. The modular RF receiver kit of claim 53, wherein the electro-optical upconversion module and the RF antenna array module are formed on corresponding substrates that are detachably connected together via a second set of RF connectors.
57. The modular RF receiver kit of claim 56, wherein each of the substrates of the electro-optical upconversion module and the RF antenna array module is a printed circuit board.

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